

# Observational constraints on the nature of very short gamma-ray bursts

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## Abstract

We discuss a very peculiar subgroup of gamma-ray bursts among the BATSE sources. These bursts are very short ( $T_{90} \leq 0.1$  s), hard, and came predominantly from a restricted direction of the sky (close to the Galactic anti-center). We analyze their arrival times and possible correlations, as well as the profiles of individual bursts. We find no peculiarities in the arrival times of Very Short Bursts (VSBs) despite their highly non-uniform spatial distribution. There is no dependence in the burst shapes on location. Bursts coming both from the burst-enhancement Galactic Anticenter region and from all other directions show considerable dispersion in their rise and fall times. Significant fraction of VSBs have multiple peaks despite their extremely short duration. Burst time properties are most likely to be consistent with two origin mechanisms: either with binary NS-NS mergers with low total masses passing through a phase of hypermassive neutron star, or with evaporation of the primordial black holes in the scenario of no photosphere formation.

**Keywords:** gamma ray bursts, primordial black holes, BATSE

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## 1. Introduction

Observations of gamma ray bursts by BATSE satellite allowed to accumulate the data set large enough for very detailed statistical studies. The distribution of the burst duration, defined as  $T_{90}$  (time-interval during which 90 per cent of the fluence is accumulated), shows clearly bi-modal distribution (Kouveliotou et al., 1993; Norris et al., 2000). Long bursts ( $T_{90} > 2$  s) show usually rather complex time-profiles, their energy spectra are generally softer, and a number of these bursts are now identified with the X-ray, optical and radio counterparts. Studies of the detected afterglows (see J. Greiner's web page<sup>1</sup>) clearly support the cosmological origin of these bursts (Costa et al., 1997; van Paradijs et al., 1997; Metzger et al., 1997). The hypernova scenario, advocated strongly by Paczynski (1995), is the most plausible explanation of this phenomenon (for a review, see Piran, 2000; Meszaros, 2002). For short bursts, the most popular scenario is compact object mergers (Lattimer and Schramm, 1976); for a review see e.g. Bulik and Belczynski (2004).

Recently, Zhang et al. (2009) discussed the dichotomy of the two GRB populations and introduced the nomenclature of Type I/II bursts, instead of the short/long bursts. This was to denote

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<sup>1</sup><http://www.mpe.mpg.de/jcg/grbgen.html>

the physically distinct categories of cosmological GRBs and to stress that the duration and hardness of the GRBs do not have to be the reliable indicators of their true physical nature.

However, the existence of a separate third group of extremely short bursts of still another origin is also likely. Cline et al. (1999) suggested that very short bursts, lasting below 0.1 s, form a separate special subgroup of short bursts. They argued that the very short bursts have euclidean spatial distribution, rather different from the spatial distribution of bursts lasting 0.1 - 2 s (as studied later e.g. by Guetta and Piran, 2005). They suggested a local origin of these shortest bursts, possibly due to the evaporation of primordial black holes. The argument was further strengthened by Cline et al. (2003), and by Cline et al. (2006) where they stress exceptional hardness of those events at the basis of KONUS data. These bursts were also found to have clearly anisotropic distribution across the sky (Cline et al., 2001).

Careful analysis of the spatial distribution of short bursts ( $T_{90} < 2$  s) was performed by Magliocchetti et al. (2003). They showed an enhanced correlation between the short bursts at angular scale of  $2-4^\circ$ , which might suggest that up to  $\sim 13\%$  of the bursts may represent repeated activity. The anisotropy in the burst distribution in a form of a spot around Galactic coordinates  $l = 115^\circ$  and  $b = 30^\circ$  was argued for by Litvin et al. (2001).

The properties of the short burst class are reviewed e.g. by Nakar (2007). The classical distinction between the short and long bursts is defined by the  $T_{90} < 2$  s, and their duration distribution peaks at  $T_{90} \approx 0.8$  s. The temporal structure of these bursts is difficult for studies, because of the low signal-to-noise ratio and limited time resolution. Therefore, any more detailed studies of the temporal structure of the short bursts, performed in the case of the long GRBs, were not carried out so far, because of the difficulty in analysis of their lightcurves.

Nakar and Piran (2002) find that most of the bursts from their sample of 33 bright events exhibit a rapid time variability on timescales much shorter than their total durations. In their sample, more than a half of bursts show at least two well separated pulses, and more than a third show rapid variability. For the single pulses, their durations range from 5 to 300 ms, with a peak around 50 ms.

The pulse properties of 55 short bursts from BATSE were also studied by McBreen et al. (2001) who found that the rise and fall times as well as the FWHM and amplitudes show lognormal distributions. The median value of the rise time of a single pulse given by these authors is 0.035 s, while for the fall time it is 0.056 and the asymmetry ratio is  $t_{\text{rise}}/t_{\text{fall}} = 0.65$ . The median total duration time for this sample was 0.095 and the median number of pulses was 2.5.

A possible sub-class of the short gamma ray bursts are the soft gamma-ray repeaters (SGR: Woods and Thomson, 2006). Their giant flares of durations about 0.1 s and hard ( $\sim 300$  keV) energy radiation are followed by a long (about 300 s), pulsating tail due to the rotation of a magnetized neutron star. The latter is much less luminous, and might easily be missed by the BATSE detector, in which case the event would be classified as a short GRB. Tanvir et al. (2005) found a correlation between the locations of short GRBs and positions of galaxies in the local Universe, indicating that 10-25% of the events originate locally, at  $z < 0.025$ . However, the signal was strongest for  $T_{90} > 0.5$  s, which is longer than a typical duration of a SGR spike. Furthermore, Ofek (2007) finds, that the upper limit on the fraction of SGRs out of the BATSE sample is  $f_{\text{SGR}} < 0.14$ .

In the present paper we revisit the problem of the very short bursts (VSB), with the aim to test their timelike characteristics. We use the BATSE sample since the number of VSB with known localization on the sky in SWIFT data (only 8 events) is not high enough for our study. In Section 2 we present our sample of very short bursts from BATSE. We study their properties such as spatial distribution, arrival times and possible correlations, as well as the profiles of individual

bursts. In Section 3 we discuss the possible origins of the special properties of our subsample and the most plausible mechanism of emission. In Section 4 we conclude our work.

## 2. Properties of the VSB from BATSE

Properties of the bursts detected by BATSE are provided by the public current catalog <sup>2</sup>. It contains 2702 events. Out of those, 2040 bursts have the measurements of  $T_{90}$  as well as the coordinates in the sky.

The subsample of short bursts (hereafter SB), with  $T_{90} < 2$ , consists of 499 bursts. Out of those bursts, 51 have  $T_{90} \leq 0.1$  s, and they further form our subsample of VSB. As shown in Cline et al. (2003), 21 of those come from 1/8 of the sky, extending from +90 to +180 deg in galactic longitude and from -30 to +30 deg in the galactic latitude (roughly in the direction of the Galactic Anticenter) so their spacial distribution is highly non-uniform. We now study other properties of this subsample which may make them different from the usual bursts and indicate their nature.

### 2.1. Arrival times

We construct a histogram of the arrival time distribution of VSB at yearly basis. The result is shown in Fig. 1. The data for all years were used, so in order to include as many bursts as possible we count the years from the beginning of the BATSE operation, i.e. the first year extends from May 1991 till April 1992 etc. There seems to be a drop in the number of VSB after 1997, and the distribution peaks around the years 1993 - 1995. However, the probability that the histogram describes the constant rate can be accepted at a 0.89 confidence level using the KS test although the straight line representing the mean rate (5.7/year) gives a poor fit to this distribution ( $\chi^2 = 13.5$  for 8 d.o.f.).

Any departure from a constant rate would be rather surprising effect. Since the bursts seem to be grouped, we also construct a histogram of the time separations between the consecutive bursts. The result is shown in Fig. 2. The expected average separation is 64 days. The observed distribution roughly corresponds to the Poisson distribution of exponential decrease, as expected if the bursts are uncorrelated in time. However, traces of enhanced small separations as well as big ones may hint toward departure from truly random arrival.

We also attempted a study of the arrival times separately for the bursts located in the Galactic Anticenter region (VSB1) and bursts located outside this region (VSB2). The number of bursts inside the region is enhanced at the beginning and seems to systematically decrease closer to the end of observation. The time distribution of bursts outside the Anticenter region seems to be more uniform. The  $\chi^2$  test of hypothesis of both distributions being constant in time give the fit quality of 11.0 and 13.0 per 8 d.o.f., for VSB<sub>1</sub> and VSB<sub>2</sub>, correspondingly. The Kolmogorov-Smirnov test gives the probability  $P = 0.567$  of the VSB<sub>1</sub> distribution and whole VSB sample being the same. The distribution of the time separations for the whole VSB set and the bursts from the Galactic Anticenter region was compared using the Kolmogorov-Smirnov test. We multiplied the time separations for bursts from the Anticenter region by the ratio of the total number of bursts in the region to the total number of VSB. After such rescaling, the two distributions are consistent at the probability level of 0.976.

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<sup>2</sup><http://f64.nsstc.nasa.gov/batse/grb/>

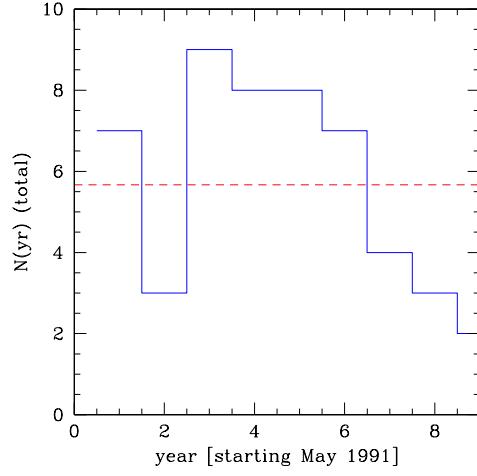


Figure 1: Distribution of the bursts arrival times for VSB.

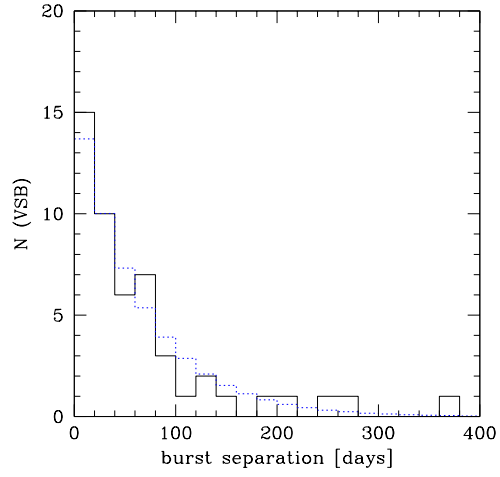


Figure 2: Distribution of the bursts separation times for VSB. Expected distribution for random arrival times is marked with the dotted histogram.

Therefore we conclude that the bursts which come from the restricted region in the Galaxy, roughly towards the Galactic Anticenter, and the other VSB are not statistically different, and their arrival is statistically consistent with being uniform in time.

## 2.2. Burst profiles

### 2.2.1. Individual profiles

We analyze the time profiles of the VSB from the event files for SB in the BATSE archive<sup>3</sup>. The requested data for 44 bursts of all VSB are available, including 19 bursts from the Anticenter region. We construct the lightcurve for each of the bursts using either all four channels, or selected channels. The individual profiles of bursts from the Galactic Anticenter region are shown in Fig. 3 (all four channels), Fig. 4 (channel 1) and Fig. 5 (channel 4), and bursts from all other regions of the sky are shown in Fig. 6 (all four channels), Fig. 7 (channel 1) and Fig. 8 (channel 4). The bursts are labeled using their BATSE trigger number.

All bursts show significant detections in the fourth channel. We determine the background in each channel separately and measure the peak countrate to the background ratio in 0.002 s bins. The ratio varies from 2.2 (for 6540) to 16.9 (for 5502). All VSB are hard, as discussed before by Cline et al. (2005) at the basis of KONUS data.

Some of the bursts are clearly double-peaked (e.g. 2464, 3910, 6486, 6788), for one of the bursts (3412) the TTE data starts after the peak, and for some bursts the data quality is so low that they cannot be used for the profile fitting analysis.

Therefore, we perform the profile fitting only for 17 bursts, using all four energy channels. Additionally, we include the burst with the trigger number 0512 since it is very short although the formally given  $T_{90}$  in BATSE catalog is somewhat higher than 0.1 s.

We subtract the background for each of the bursts separately, and the background level is determined from the data points separated by more than 0.15 s from the burst maximum, and we renormalize the bursts to have maximum at 1.0 for all events.

We fit the normalized profiles using double exponential fit:

$$\begin{aligned} f(t) &= \exp((t - t_0)/t_{\text{rise}}) & \text{for } t < t_0 \\ &= \exp(-(t - t_0)/t_{\text{fall}}) & \text{for } t > t_0 \end{aligned} \quad (1)$$

and the three parameters,  $t_{\text{rise}}$ ,  $t_{\text{fall}}$ , and the shift  $t_0$  are fitted to the data. The time axis for each burst is defined in such a way that  $t = 0$  corresponds to the peak maximum (or to the first peak, if two equal count-rate peaks exist). We also made fits with  $t_0 = 0$ , i.e. with the change from rise to fall fixed at the maximum of the burst. However, better  $\chi^2$  is in general given by fits with  $t_0$  as a free parameter. In case of one of the bursts (BATSE trigger number 3904), a freedom of  $t_0$  shifts the peak considerably and the fit is problematic due to the fact that the background before the burst is much higher in this case than after the burst. Both fits are presented: selected bursts, normalized and background-subtracted, are shown in Figs. 9 and 10, for bursts from the Galactic Anticenter region and for those from the other parts of the sky, respectively. In the further analysis we use the fit with arbitrary  $t_0$  for all bursts for consistency.

Almost all bursts show certain amount of asymmetry, with faster rise time and slower decrease. The median of the rise timescale is 0.0040 s, the median of the fall timescale is longer, 0.0110 s, and the median value of the ratio of these two timescales is 0.4. Therefore, the

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<sup>3</sup><http://cossac.gsfc.nasa.gov/batse/batseburst/tte/ascii.html>

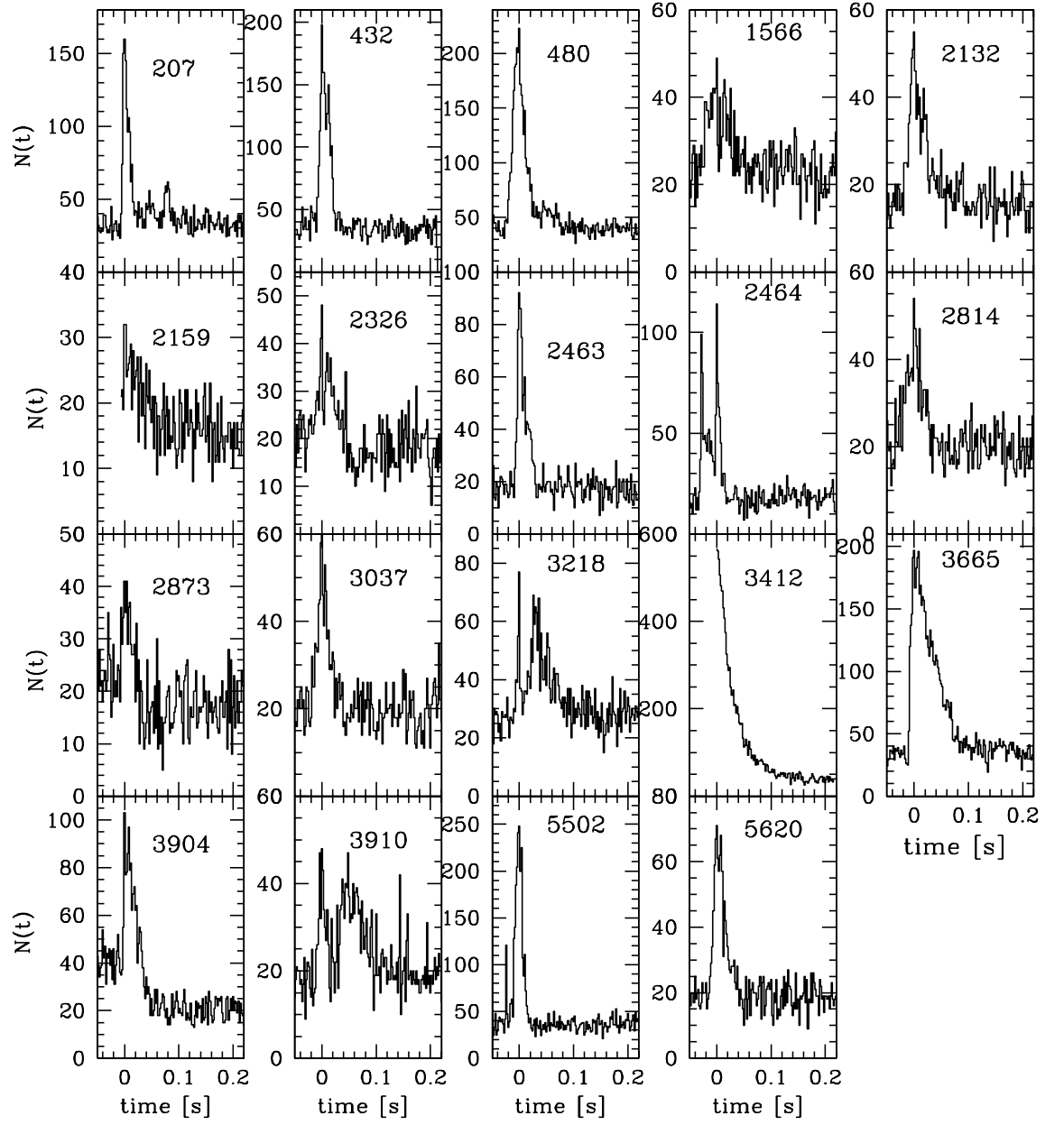


Figure 3: Profiles of the VSB from the Galactic Anticenter region in channels 1 - 4. Count rate given for 0.002 s bins.

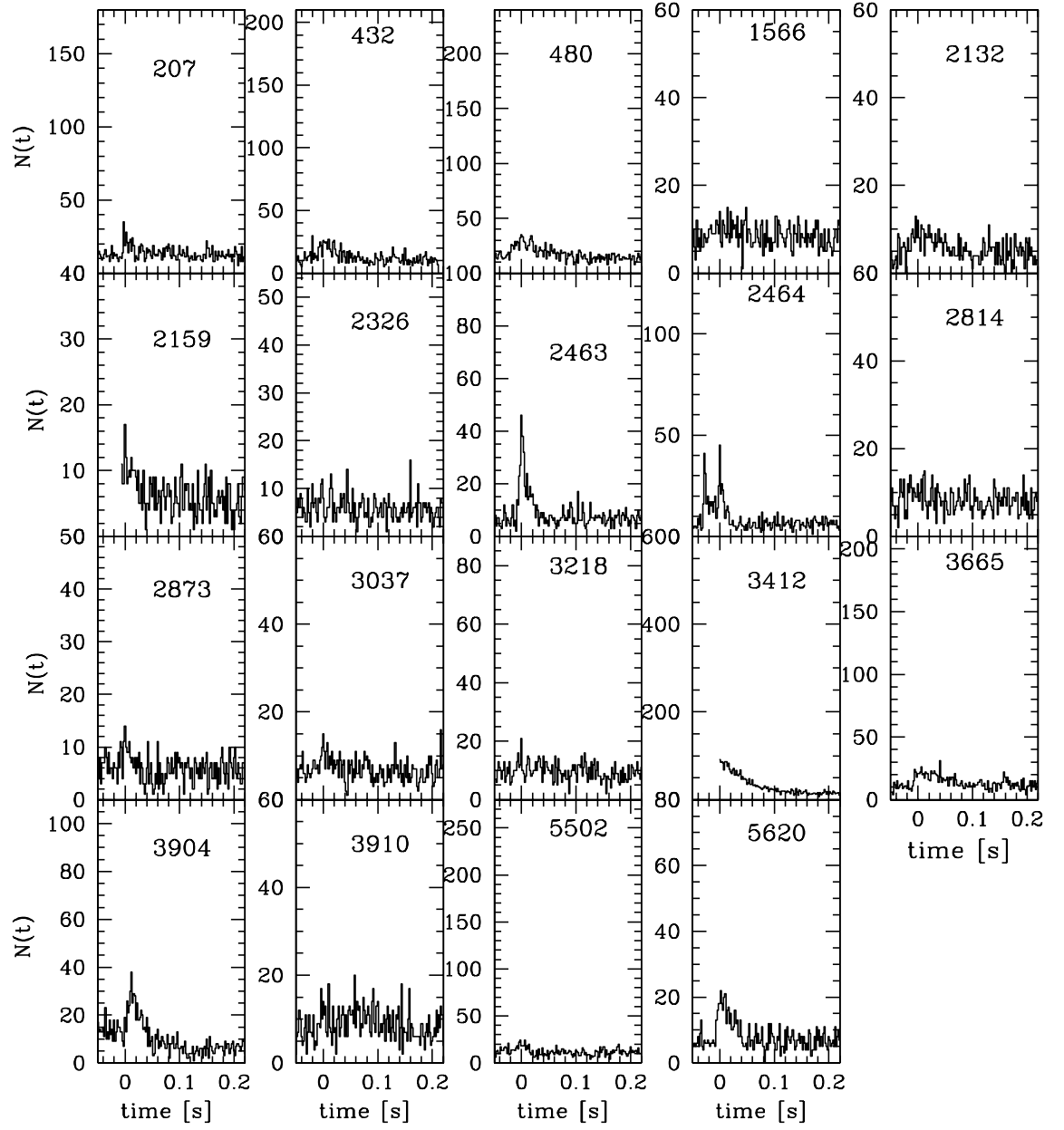


Figure 4: Profiles of the VSB from the Galactic Anticenter region in channel 1. Count rate given for 0.002 s bins.

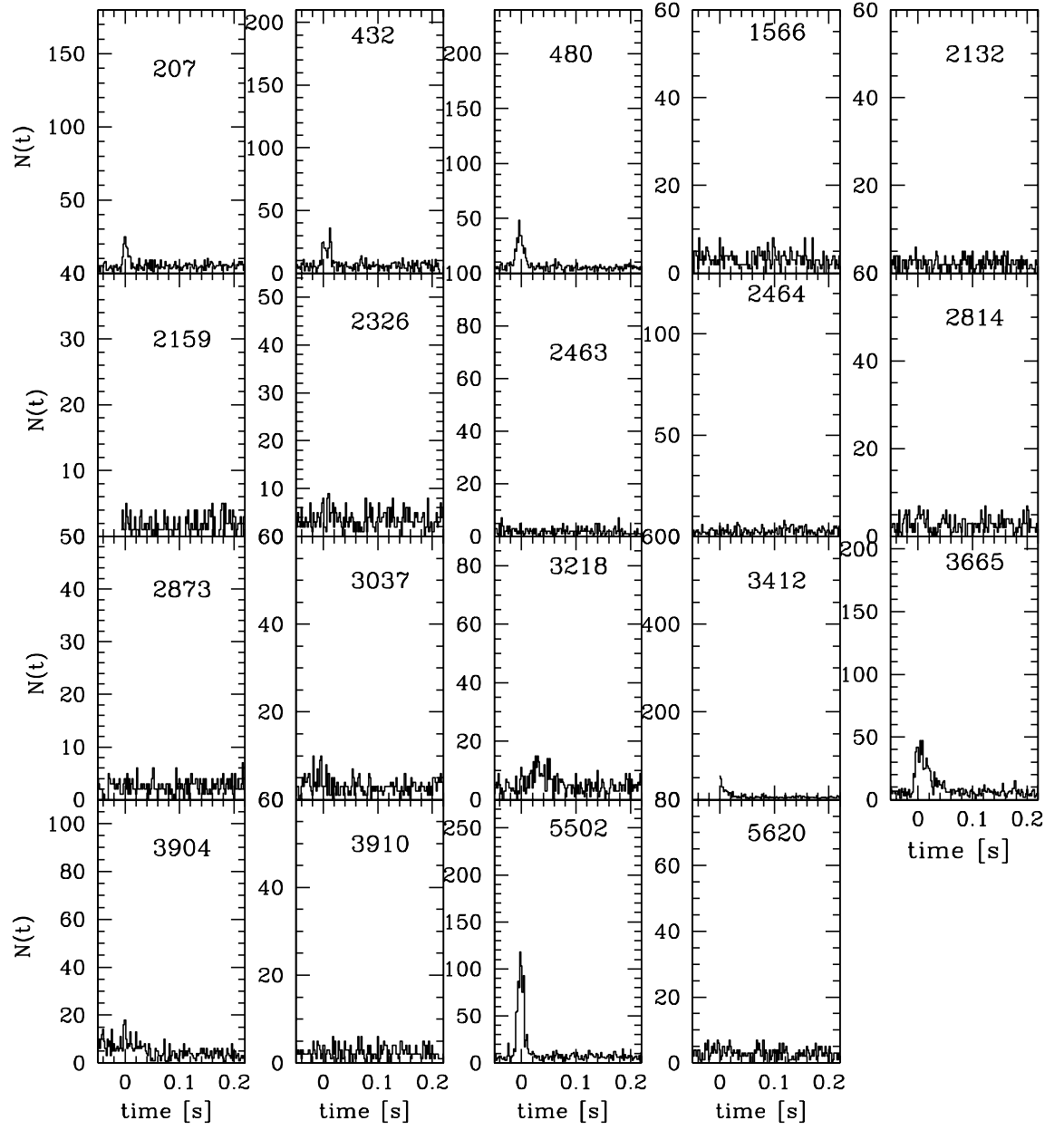


Figure 5: Profiles of the VSB from the Galactic Anticenter region in channel 4. Count rate given for 0.002 s bins.



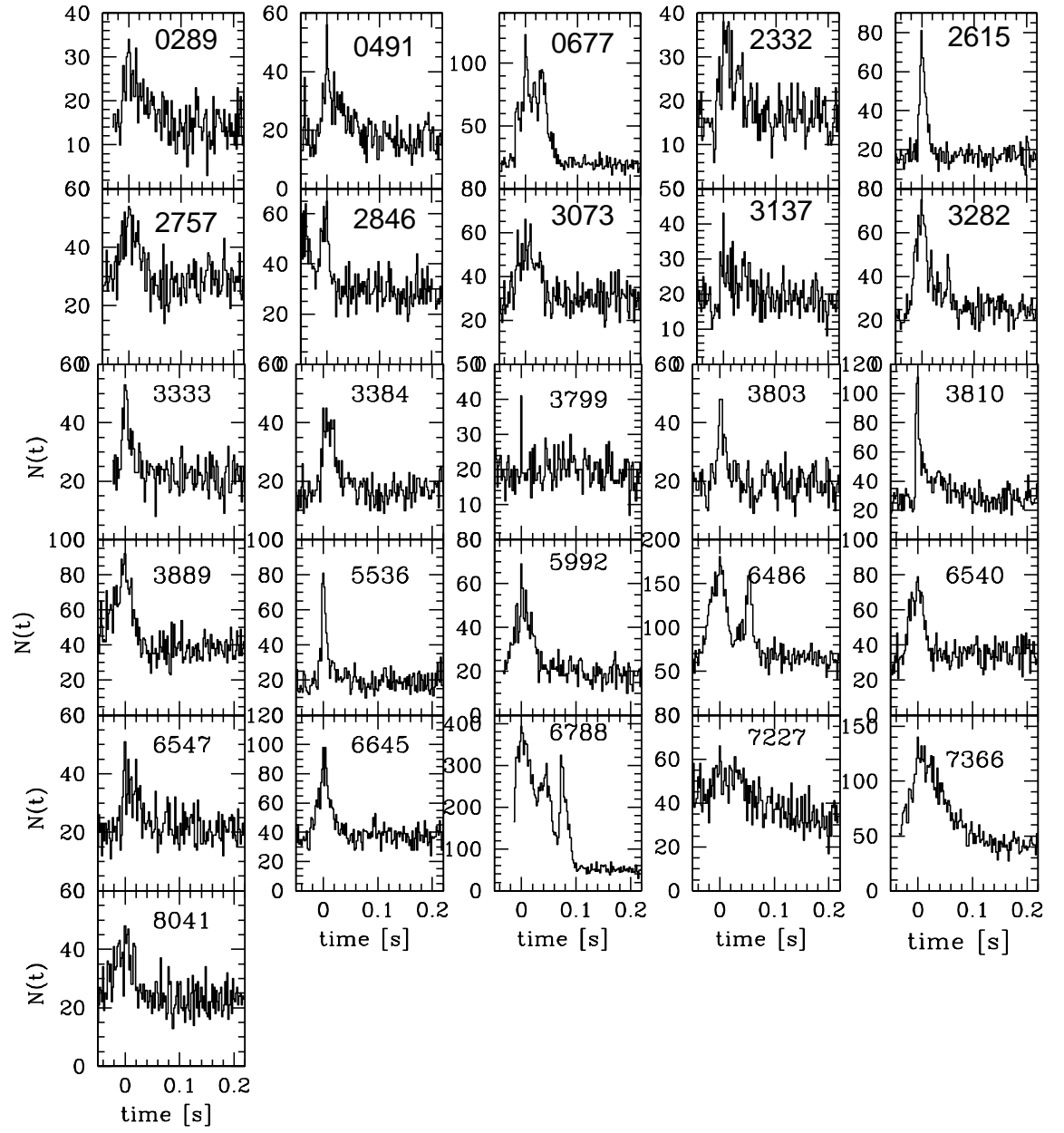


Figure 6: Profiles of the VSB from outside the Galactic Anticenter region in channels 1 - 4. Count rate given for 0.002 s bins.

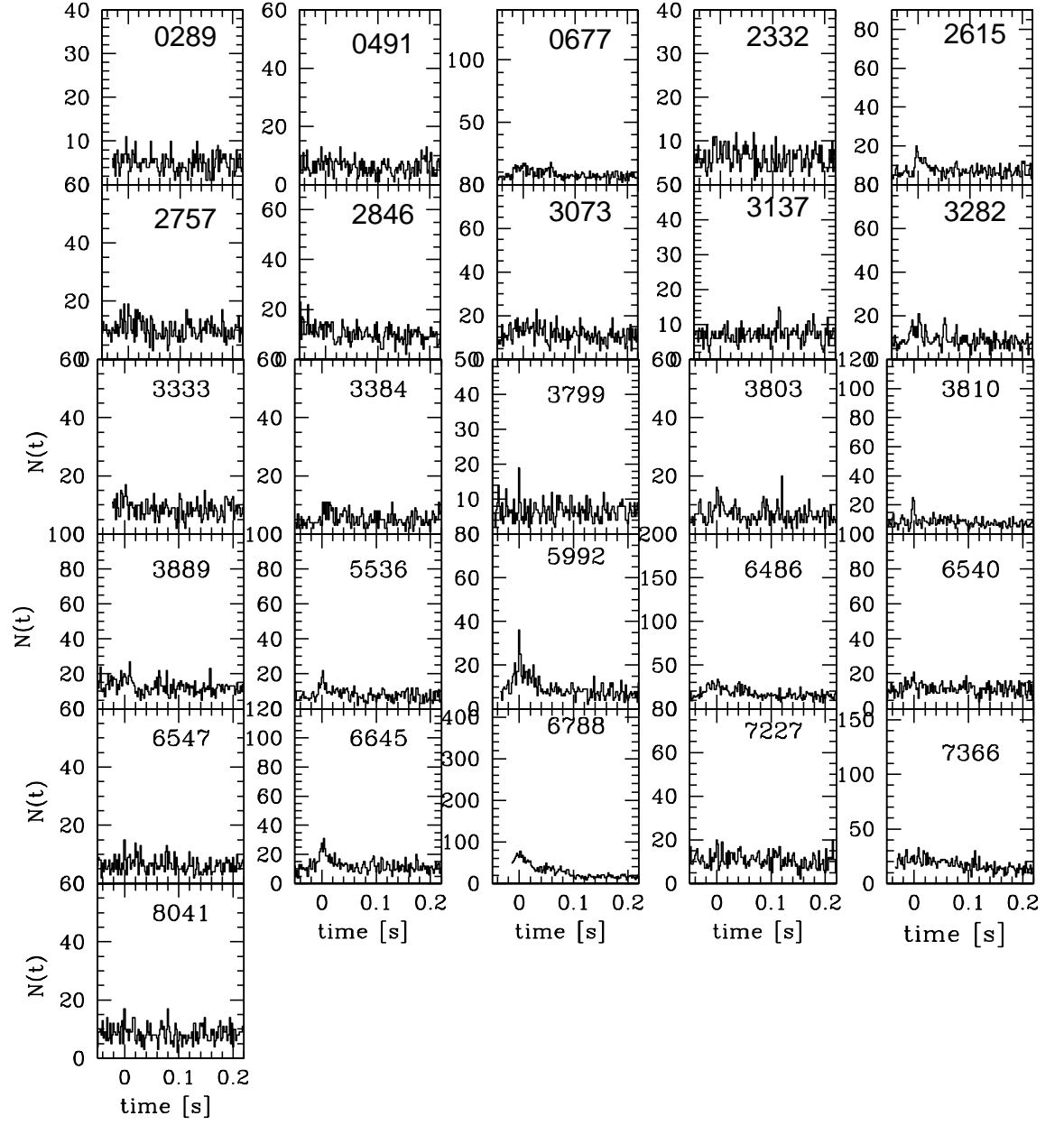


Figure 7: Profiles of the VSB from outside the Galactic Anticenter region in channel 1. Count rate given for 0.002 s bins.

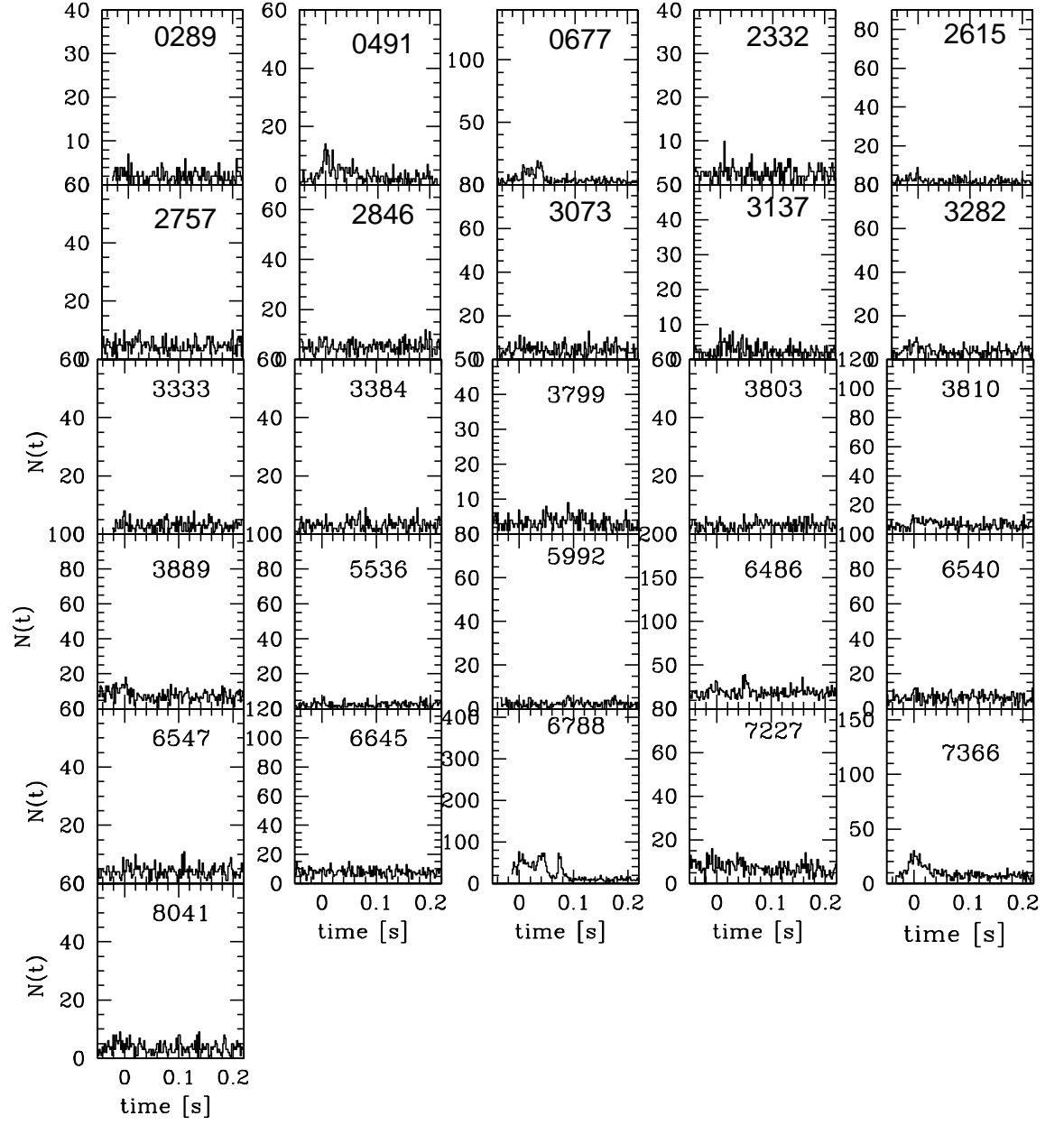


Figure 8: Profiles of the VSB from outside the Galactic Anticenter region in channel 4. Count rate given for 0.002 s bins.

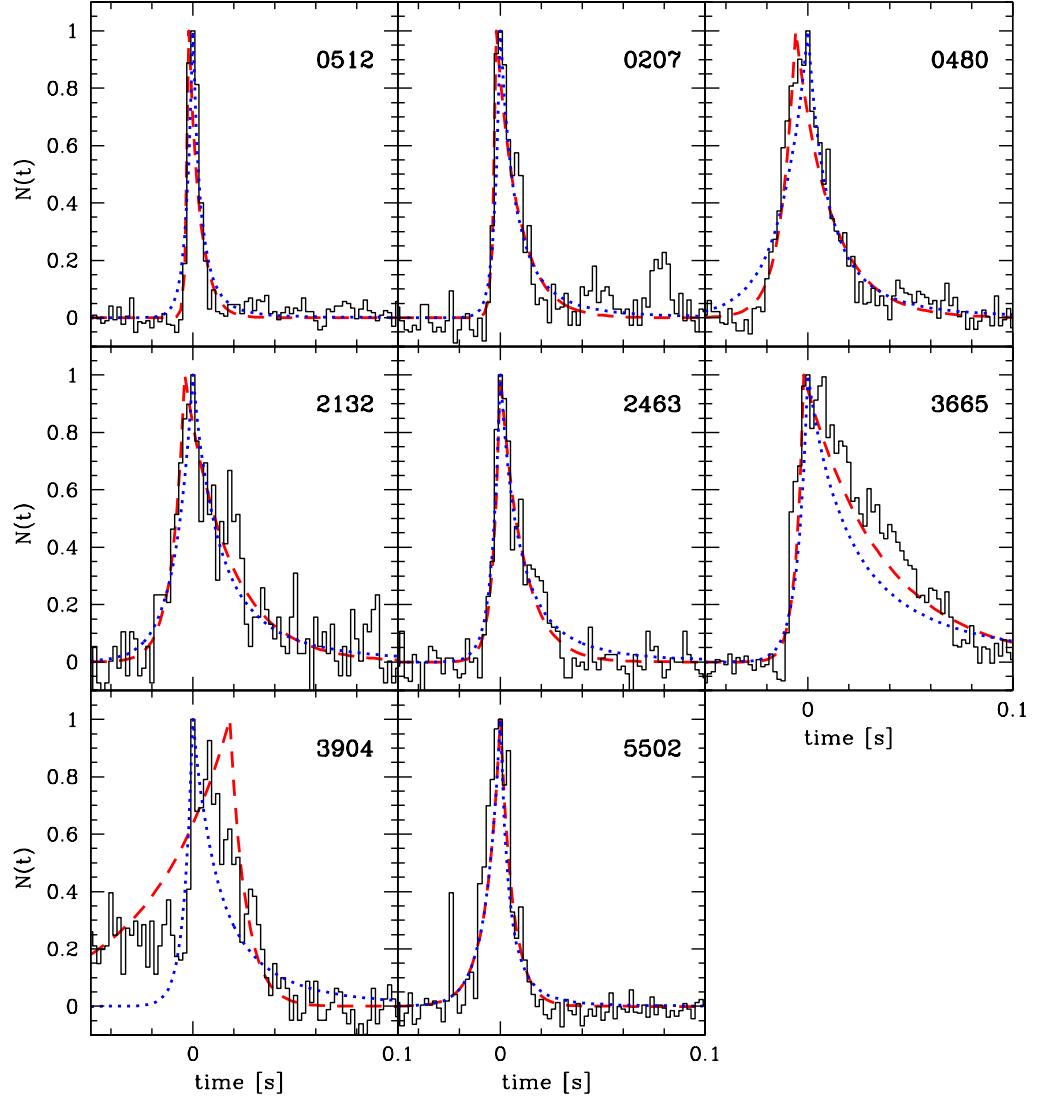


Figure 9: Normalized background-subtracted profiles in 1 - 4 energy channels of the selected VSB from the Galactic Anticenter region in 0.002 s bins. The short-dashed line shows the double exponential fit to the burst profile with fixed  $t_0 = 0$ , while the long-dashed line shows the fit with  $t_0$  being a fitting parameter.

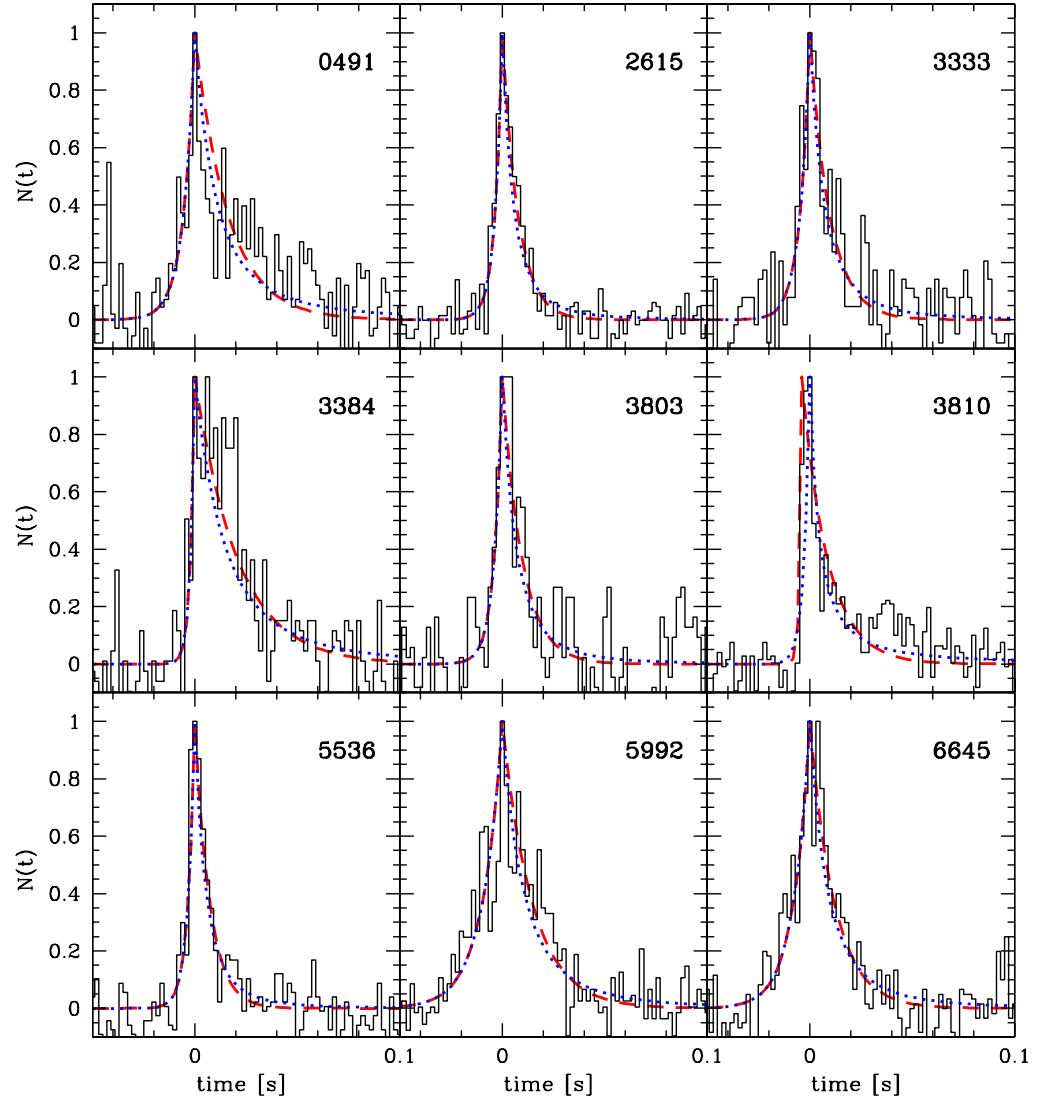


Figure 10: Normalized background-subtracted profiles in 1 - 4 energy channels of the selected VSB from outside of the Galactic Anticenter region in 0.002 s bins. The short-dashed line shows the double exponential fit to the burst profile with fixed  $t_0 = 0$ , while the long-dashed line shows the fit with  $t_0$  being a fitting parameter.

Table 1: Properties of single VSB with good S/N ratio

BATSE trigger	$t_{rise}$ [s]	$t_{fall}$ [s]	$t_0$ [s]	$\chi^2/dof$
0512	$0.0011^{+0.0003}_{-0.0004}$	$0.0053 \pm 0.0005$	$-0.002 \pm 0.002$	1.49
0207	$0.0014^{+0.0006}_{-0.0005}$	$0.0108 \pm 0.0015$	$-0.002 \pm 0.002$	1.27
0480	$0.0068^{+0.0009}_{-0.0009}$	$0.0172 \pm 0.0014$	$-0.006 \pm 0.002$	1.35
2132	$0.0061^{+0.0023}_{-0.0022}$	$0.0212 \pm 0.0041$	$-0.004 \pm 0.002$	1.03
2463	$0.0035^{+0.0010}_{-0.0009}$	$0.0110 \pm 0.0018$	$0.0 \pm 0.002$	1.31
3665	$0.0038^{+0.0006}_{-0.0007}$	$0.0379 \pm 0.0007$	$-0.002 \pm 0.002$	1.72
3904	$0.0397^{+0.0050}_{-0.0048}$	$0.0076 \pm 0.0017$	$0.018 \pm 0.002$	2.17
5502	$0.0071^{+0.0007}_{-0.0008}$	$0.0060 \pm 0.0008$	$0.0 \pm 0.002$	2.26
0491	$0.0056^{+0.0023}_{-0.0022}$	$0.0161 \pm 0.0046$	$0.0 \pm 0.004$	1.28
2615	$0.0036^{+0.0011}_{-0.0011}$	$0.0076 \pm 0.0017$	$0.0 \pm 0.002$	1.06
3333	$0.0048^{+0.0030}_{-0.0024}$	$0.0097 \pm 0.0038$	$0.0 \pm 0.003$	1.12
3384	$0.0021^{+0.0022}_{-0.0021}$	$0.0207 \pm 0.0049$	$0.0 \pm 0.002$	1.01
3803	$0.0040^{+0.0023}_{-0.0023}$	$0.0096 \pm 0.0036$	$0.0 \pm 0.003$	1.38
3810	$0.0010^{+0.0003}_{-0.0010}$	$0.0126 \pm 0.0025$	$-0.004 \pm 0.002$	1.29
5536	$0.0034^{+0.0011}_{-0.0012}$	$0.0072 \pm 0.0019$	$0.0 \pm 0.002$	1.17
5992	$0.0098^{+0.0026}_{-0.0027}$	$0.0146 \pm 0.0031$	$0.0 \pm 0.003$	1.24
6645	$0.0080^{+0.0024}_{-0.0022}$	$0.0120 \pm 0.0028$	$0.0 \pm 0.002$	1.00

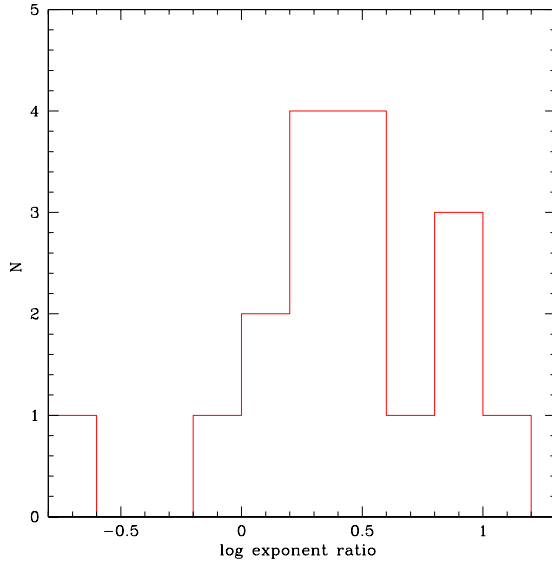


Figure 11: Histogram of the exponent ratio  $r = t_{fall}/t_{rise}$  with  $t_{rise}$  and  $t_{fall}$  defined on the rising and falling part of the lightcurve of selected VSB

timescales on average are much shorter than found by McBreen et al. (2001) for short bursts. This is because they included also short bursts with  $T_{90} > 0.1$  s. The timescale ratio indicates larger asymmetry in selected VSB but this effect might be due to some contribution of double-peak events even in the selected bursts. For example, 2132 seems to have traces of a secondary maximum at  $t \approx 0.015$  s, and 3665 may actually be a multiple case. In Fig. 11 we show the distribution of the ratios of the two exponents in the two-exponent fit to the selected bursts (Equation 1). The histogram has two peaks, one around  $r = t_{\text{fall}}/t_{\text{rise}}=2.5$  ratio and one around the ratio of  $r \approx 10$ . However, the effect of bimodality is not significant, taking into account the small number of bursts.

We checked the burst profiles in all four energy channels for possible time delays. In some bursts the peak in the first channel was earlier than in the remaining three channels (a negative lag in trigger no. 0207 by 2 ms; in 0289 by 4 ms; in 0491 by 8 ms; in 2326 by 2 ms; in 3910 by 4 ms), and in a few cases the peak in the channel 4th was delayed (a positive lag in trigger no. 0432 by 12 ms; in 2159 by 2 ms; in 2332 by 8 ms; in 3384 by 8 ms; in 3803 by 6 ms; in 5536 by 4 ms). In other bursts, the peak in channel 4 was advanced (a negative lag in trigger no. 2463 by 2 ms; in 3037 by 4 ms; in 3810 by 2 ms; in 5502 by 2 ms; in 5620 by 4 ms; in 6547 by 2 ms; in 7227 by 2 ms). In two bursts (2757 and 3073) two peaks in channel 4 are seen. In all other bursts the peaks in all energy channels coincided (with the accuracy of the 2 ms time bin) within the statistical error of one sigma. However the poor countrate prevents us from the detailed fitting of the profiles in separate energy channels and the quantitative measurement of the time delays was not possible, and the lags mentioned above are likely insignificant.

We also compared the fluxes of the bursts within the Anticenter region and outside it. The bursts seen towards the Anticenter are somewhat brighter (with median countrate of  $77 \pm 5$  cts in 0.002 bins without background subtraction) than the remaining bursts (median of  $66 \pm 6$  cts), although the background itself determined close to VSB is actually slightly lower in the direction of the Anticenter (Cline et al., 2005, 25.0 cts vs. 27.6 cts in 0.002 bins). However, since errors are large the difference is not highly significant.

### 2.2.2. Composite profiles

In order to overcome the problem of low S/N ratio in most of the bursts we also construct the composite burst profile.

The background-subtracted lightcurve is later normalized by its maximum value and shifted, so the maximum is at  $t = 0$ . All lightcurves in all four channels are added, and the result divided by the number of lightcurves included. The resulting composite profile is shown in Fig. 12.

The profile shows significant asymmetry, characteristic also for longer bursts. Its shape is well represented by the exponential rise with the timescale of 0.0079 s, and approximately represented by the exponential decay time of 0.0171 s.

These timescales are much shorter than the average rise and decay timescales of single pulses in a sample of SB ( $\sim 0.036$  s and  $\sim 5.5$  s correspondingly, McBreen et al., 2001) but fall within the broad distribution of these parameters in the sample. Therefore, VSB show basically the same trend as seen in all gamma ray bursts (Band et al., 1997; Norris et al., 2000) although the timescales involved are clearly much shorter.

Better fit to the decay phase, however, is provided by the function

$$f(t) = \frac{1}{(1 + t/\tau)^n} \quad (2)$$

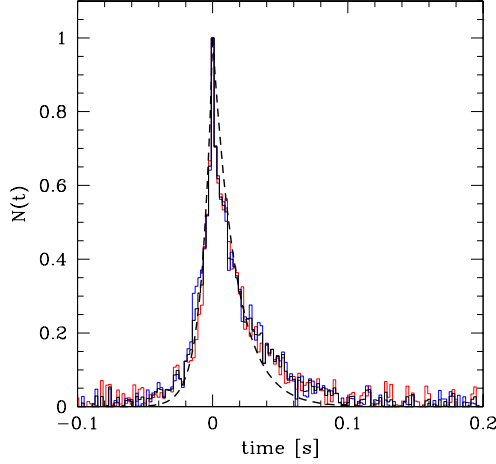


Figure 12: Composite burst profiles for all VSB (black line), for bursts from the Galactic Anticenter region (red line) and for bursts from outside that region (blue line). The analytical fit (dashed line) is given by Eq. 1. Better fit for the decay part is provided by Ryde & Svensson function (Eq. 2; see text)

with index  $n = 2.62$  and the decay timescale  $\tau = 0.0319$  s. Ryde and Svensson (2002) analyzed 22 bright pulses in long bursts using this description and they found a bi-modal distribution. Although most of bursts are well represented by  $n = 1.0$ , there was a secondary enhancement around  $n = 3.0$ . It is therefore interesting to note that VSB may show some similarity to the latter subclass of pulses.

If we choose only the energy range 50 - 300 keV (i.e. the channels 2+3) for the analysis the results are: timescale of the exponential rise 0.0093 s, exponential decay 0.0195 s, with again a much better fit to the decay part given by Eq. 2, with  $n = 2.44$  and  $\tau = 0.0319$  s.

We searched for a correlation between the burst asymmetry and the burst hardness defined as a ratio of the peak countrate in the channel 4 to the total peak countrate. However, we do not detect a significant trend, perhaps due to the low quality of the data.

We also calculated the composite burst profile in all four channels separately. We used the fixed time grid determined for the total profile (e.g. for combined 1 - 4 channels). In this way we allowed for advancement or a delay of the burst maximum with respect to the position of the maximum in the average profile from all four channels. The result is shown in Fig. 13. Burst peaks still coincide within the energy grid accuracy (0.002 s). We cannot increase the time resolution since the number of available photons is not large enough. The graph shows, however, that the profile in 4th energy channel is the narrowest.

We also compare the shape of the composite pulse profile to specific prediction of the model of evaporation of a primordial black hole (for basic reviews, see e.g. Carr et al., 1976, 2005).

The time profile of the pulse produced due to the black hole evaporation can be derived from the temperature of the black body radiation, which in the Hawking process is inversely dependent



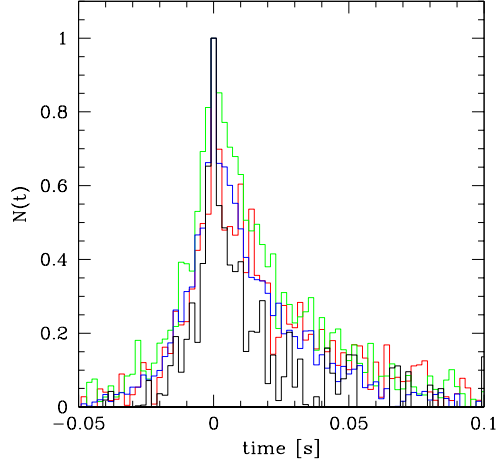


Figure 13: Burst composite profiles for all VSB, for four energy channels separately, normalized to 1 for each energy channel: Red:channel 1, Green:channel 2, Blue:channel 3, Black:channel 4. The narrowest profile is seen in channel 4.

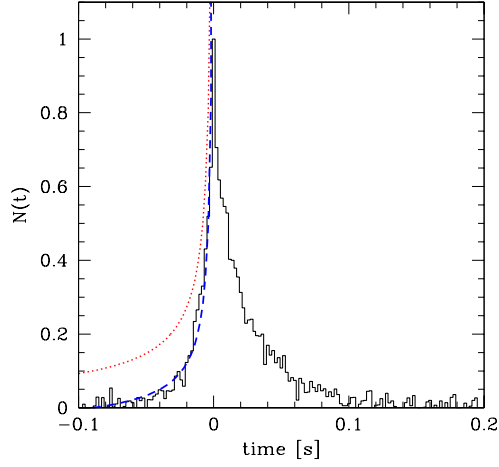


Figure 14: Composite burst profile for all VSB (black line) with the analytical fits given by Eq. 6. The dotted line shows the fit with normalization calculated from the luminosity integral, while the dashed line shows the profile with normalization fitted to the background level.

on the black hole mass:

$$T = \frac{\hbar c^3}{8\pi G k M} = 10^{16} \frac{1}{M[g]} [MeV]. \quad (3)$$

The luminosity is then given by:

$$L = -\frac{dE}{dt} = \frac{d(Mc^2)}{dt} = -\sigma T^4 4\pi R^2, \quad (4)$$

where  $R = 2GM/c^2$  is the Schwarzschild radius. From the above relation, one can see that the luminosity is inversely proportional to the square of the black hole mass,  $M^2$ . The mass dependence on time is found by integrating  $dM/dt$  from the time  $t < 0$  to  $t_0 = 0$ , when the black hole is completely evaporated. The lifetime of a black hole till evaporation is

$$t \propto M^3, \quad (5)$$

and the luminosity from Eq. 4 can be expressed as a function of time:

$$L(t) \propto Ct^{-2/3}. \quad (6)$$

The luminosity profile goes to infinity at  $t = 0$ . Nevertheless, the integrated luminosity is finite, so we can derive the normalization of the lightcurve based on the integral before the burst maximum being equal to that after the maximum.

The fit of the function given by Eq. 6 to the composite profile is shown in Figure 14. Two curves represent the fits with (i) the normalization derived from the integrated luminosity (i.e. the integral of the analytic curve and the background-subtracted curve coincide) and (ii) the normalization arbitrarily fitted to the background level. The first method overpredicts significantly the luminosity of the burst before the peak. However, since the evaporation formula above does not give the time profile after the peak, the background determination may be biased by enhanced emission before as well as after the peak. This argument justifies the second approach, and in this case the fit to the rising part of the profile is good.

The approach used above neglects the change of the spectral shape in time. It can be justified in the following way. The temperature of the black body emission during the final stage ( $\sim 0.1$  s before complete evaporation) is of the order of 15 TeV, and at that stage a fireball is already formed. In other words, the evaporating plasma (photons, electron-positron pairs and heavier particles) is no longer optically thin, because a simple estimate of the total thickness for electron scattering indicates a depth of the order of 1000. The following creation of electron-positron pairs is efficient and the final temperature of the radiation reaching an observer saturates at the energy threshold for this process. If this approximation is indeed justified then there is no temperature variation with time at the final stages and only the luminosity varies. Therefore the specific energy-dependent sensitivity of an instrument does not influence the shape of the lightcurve.

Also, if we assume that indeed the emitted particles do not interact, the peak emission of photons is at very high energies, well above the instrument response. The detected photons would then come from the low energy tail, again perhaps weakly dependent on time apart from normalization.

However, if the thermalization is not full, and for example pion processes are important as discussed in several papers (e.g. Maki et al., 1996; Kapusta, 1999; Carr et al., 2010), or if the relativistic boosting of the fireball varies with time, there may be a spectral hardening effect and in this case our approach is too simplistic. However, no specific models of time-dependent spectral evolution of a fireball are available yet.

### 3. Discussion

Very Short Gamma-ray Bursts were proposed to originate as a result of evaporation of the primordial black holes (Cline et al., 1999). In this paper we carefully studied the spectral and temporal properties of VSB from BATSE with the aim to test whether they are likely to have a different origin than the other short gamma ray bursts.

The burst duration for VSB is much shorter than the duration of short bursts, or of mixed samples with VSB and short bursts included (e.g. McBreen et al., 2001). The shortest rise time is only 5.3 ms. However, otherwise they seem to be the scaled-down analogues of short bursts. They are typically asymmetric, with faster rise than the decay time. Moreover, a number of VSB still consist of two or more subpulses, so the complex structure typical for longer bursts is visible even in this class.

Significant fraction of VSB (21 out of 51) come from 1/8th of the sky located roughly in the direction of the Galactic Anticenter region, extending from +90 to +180 deg in galactic longitude and from -30 to +30 deg in the galactic latitude (Cline et al., 2003). The significance of this anisotropy has been estimated by (Cline et al., 2001) to be  $1.4 \times 10^{-6}$ , and by Piotrowski et al.<sup>4</sup>, (unpublished) to be a few times  $10^{-5}$  using the factorial analysis. Bursts coming from the Anticenter region are slightly brighter but the effect is at the level of 2 sigma, and the distribution of the arrival times of both classes is statistically consistent with uniform.

The enhancement of the number of VSB BATSE bursts in the direction of the Galactic Anticenter is clearly a puzzle. On the other hand, there are several interesting observations indicating the exceptional properties of that region. Roughly at that direction there is one of the richest known regions of star formation in the Galaxy, with over 800 HII regions, many Wolf-Rayet stars, including the richest Cygnus OB2 association (see Kraemer et al., 2010, for Cygnus-X Spicer Legacy Survey). The COMPTEL A1 26 survey indicated a clear enhancement in the Anticenter region also likely related to nucleosynthesis activity (see e.g. Diehl, 2001). An excess of the TeV cosmic rays from the general direction of the heliotail, also close to the Galactic Anticenter, has been reported by Abdo et al. (2008). However, (Salvati and Sacco, 2008) argued against the heliotail origin. Similar claims of such cosmic ray anisotropy has also been done in the past, but with the argument in favor of the connection with heliotail based on annual trend (Fujimoto et al., 2001). Interesting possibility of correlations between the VSB and the regions of enhanced correlation between the microwave background and the diffuse gamma rays above 1 GeV has been considered by Jedrzejczak et al. (2007).

For the energy distribution, VSB are much harder than short bursts (Cline et al., 2005). However, this effect can be considered as a continuation of a more general trend of bursts being harder when shorter, including the long-soft GRBs (see e.g. Zhang et al., 2009). We did not find any significant time delays between the peak emission in the four energy channels and we can only put an upper limit of 2 ms for such a delay. It is interesting to note that studies of long bursts showed that there is an anticorrelation between the lags and the total burst isotropic luminosity (Norris et al., 2000):

$$L_{\text{pk}} \approx 1.3 \left( \frac{\tau}{0.01 \text{ s}} \right)^{-1.15} [10^{53} \text{ erg s}^{-1}] \quad (7)$$

It was interpreted by Salmonson and Galama (2002) as due to the variation in jet opening angles. They also suggested that measurements of variability or of spectral lags can then be used as a crude distance indicator for the GRBs. However, in the case of short bursts, both positive and

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<sup>4</sup><http://www.lip.pt/events/2006/ecrs/proc/ecrs06-s5-10.pdf>

negative lags were reported (Gupta et al., 2002), usually on the order of 50 ms. Therefore, the absence of measurable lags in combined profiles of VSB may not be surprising.

The distribution of the GRBs in space shows that the cosmological effects are playing the important role. The mean  $V/V_{\max}$  value for the sample of long bursts was 0.282, while for the short GRBs it was somewhat larger, equal to 0.390 (Guetta and Piran, 2005; Guetta, and Piran (2006). In this respect, the value estimated by Cline et al. (1999) to be 0.52, and indicating the euclidean distribution of the VSBs, seems to be a continuation of this trend. The shorter the bursts, the more locally they are observed. Based on our present study, is still not clear whether this might be the effect of a yet another different progenitor type, or rather a selection effect.

### 3.1. VSB from SWIFT

The number of very short events ( $T_{90} < 0.1$  s) detected by the SWIFT satellite is small so they are not suitable for statistical analysis. Nevertheless, these high quality data may shed some light onto the nature of such events. In Table 2 we list all the events with  $T_{90} < 0.1$  s, and in addition two more with  $T_{90}$  just above 0.1. Out of those 10 sources, none is located in the Anticenter region found overpopulated with VSB in the BATSE data. Three bursts now populate another of the 8 sky regions discussed by Cline et al. (2001), located between 0 and 90 deg of the Galactic longitude, and -30 and +30 deg of the Galactic latitude. The probability of such coincidence is 0.09 which cannot be considered as highly significant departure from uniform distribution.

Candidate afterglow/host galaxies were claimed for some of those bursts but fading of the optical counterpart was never detected for any of those sources. For 100206A an optical counterpart was found by Levan et al. (2010). The spectroscopy obtained with the Keck telescope revealed the presence of a galaxy at the indicated location, with the redshift 0.41 (Cenko et al., 2010), and the projected offset of the burst from the galaxy center was  $\sim 35$  kpc. The burst GRB 060502B has been found to coincide with  $z = 0.287$  galaxy, and the implied offset from the center was  $73 \pm 19$  kpc (Bloom et al., 2007). The event 050509B was very bright in X-rays and well localized, but again no fading optical/near infrared/millimeter counterpart was found. The source has been tentatively connected with  $z = 0.225$  galaxy, a member of a galaxy cluster (Gehrels et al., 2005; Hjorth et al., 2005; Castro-Tirado et al., 2005). The projection distance in this case is  $\sim 33$  kpc. However, the X-ray afterglow measured by Swift XRT in this source starting from 62 s after the gamma burst was detected up to 300 s after the burst (Rol et al., 2005; Bloom et al., 2005), and the X-ray luminosity was decreasing exponentially, with an index of  $\sim 1.3$ , implying the decay time below 60 s. The relatively long duration of this signal in comparison with the prompt gamma-ray emission may indeed support some (relativistic?) ejection of material which later undergoes cooling. Lee et al. (2005) found this timescale roughly consistent with the binary merger scenario.

The comprehensive information on each of the bursts can be found through the internet <sup>5, 6</sup> for each of the bursts. The burst profiles viewed in 2 ms bins used for BATSE data analysis are usually single, although some substructure may be present in GRB 050925, GRB 070810B and GRB 090417A.

### 3.2. Possible mechanism of emission

The tentative continuity of the burst properties from long bursts through short to VSB does not imply the same mechanism behind those events: long bursts are due to hypernova phe-

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<sup>5</sup><http://www.swift.ac.uk>

<sup>6</sup><http://gcn.gsfc.nasa.gov>

Table 2: Properties of VSB from Swift

name	$t_{90}$ [s]	gal. longitude	galactic latitude	redshift
050509B	0.073	182.90828684	86.15594183	0.225 ?
050925	0.070	72.30514279	-0.07005621	-
051105A	0.093 <sup>a</sup>	59.86196122	28.78790172	-
060502B	0.131	81.59665275	23.53577034	0.287 ?
070209	0.090	259.76518949	-57.02797996	-
070810B	0.080	116.37637070	-53.85090173	-
070923	0.05	295.85521498	24.12470763	-
090417A	0.072	173.46586705	-61.03545070	-
090515	0.036	232.46491111	60.44320773	-
100206A	0.12	166.88023385	-37.72547634	0.41 ?

<sup>a</sup>  $T_{90}$  = 0.028 according to (Cummings et al., 2005), other burst parameters according to on-line SWIFT catalog [http://heasarc.gsfc.nasa.gov/docs/swift/archive/grb\\_table/index.php](http://heasarc.gsfc.nasa.gov/docs/swift/archive/grb_table/index.php).

phenomenon, short burst are due to mergers of compact objects in binary systems (neutron stars or black holes), and the origin of the VSB is still waiting for explanation. Two possibilities are natural to consider: a binary merger but with (for some reason) exceptionally short timescale and evaporation of primordial black holes. We consider those two scenarios below.

### 3.2.1. binary merger

The merger of binary systems NS-NS and NS-BH were modeled by a number of authors (for the review, see e.g. Faber, 2009). The expected duration of the BH-NS merger events is frequently somewhat longer than the shortest timescale  $T_{90}$  of a VSB (in our sample, the shortest VSB is 5.3 ms, see Table 1; in the SWIFT data the shortest burst found, GRB 090515, had  $T_{90}$  of 36 ms).

The Newtonian simulations of the BH-NS merger (Lee and Kluzniak, 1999) were run for the mass ratio  $q = M_{\text{NS}}/M_{\text{BH}} = 0.1 - 1.0$ , and showed that after about 30 ms the neutron star was disrupted and formed a torus of a mass of few tenths of the solar mass. The accretion rate at that moment was on the order of 2-6 solar masses per second, and therefore the expected lifetime of the torus feeding the black hole in during the GRB event was  $\tau_{\text{accr}} = M_{\text{disc}}/\dot{M} = 40 - 60$  ms. The relativistic simulations of Setiawan et al. (2006), performed for a range of black hole spin parameters, followed the evolution of such torus with a mass of 0.01-0.2  $M_{\odot}$ . They showed that in the end of the run, after 40-70 ms the mass of the torus is about half of the initial mass and the accretion rate drops to about 0.2-0.6  $M_{\odot}/\text{s}$ . Therefore the lifetime of the central engine will be much longer than that.

In merger event the duration of the phenomenon in the case of neutron star - black hole merger is fixed by the distance between the two at the phase of the neutron star tidal disruption and later by the viscosity operating within the accretion disk.

In numerical simulation of Shibata and Taniguchi (2008) using  $\Gamma$ -law equation of state with  $\Gamma = 2$  the disruption of the neutron star happened close to the innermost stable circular orbit. The disruption process lasts for about 5 ms and after that time the unswallowed remnants of the star form a torus of the size of about 50 km. The further stage of the accretion onto a black hole lasts

about 100 ms for a  $3 M_{\odot}$  black hole, according to Janiuk et al. (2004) but those computations adopted  $50 R_S$  for the size of the outer edge of the disk. If those computations are rescaled to  $6 R_S$  the duration of the accretion phase may possibly be considerably shorter, consistent with the decay timescale of the shortest burst.

Short duration of the burst would then be provided by a small value of the black hole mass in the binary - larger black hole than  $3 M_{\odot}$  would give too long burst duration. Thus in a natural way VSB would be connected with small mass black holes, would be fainter in the absolute luminosity and thus statistically less distant than short bursts. This last effect might explain the lack of cosmological effects in their  $V/V_{\max}$  distribution.

On the other hand, computations by Metzger et al. (2008) suggest that the duration of the NS-BH merger is longer if the disk mass (and in consequence, the total luminosity) is smaller, and for small disk masses ( $0.03 M_{\odot}$ ) the event lasts above 0.1 s, up to 1 s. If so, the VSB, likely to be intrinsically faint, are not consistent with VSB properties.

Another merger scenario is possible if two neutron stars merge, and the total mass of the system is small. In this case it is probable that a differentially rotating hypermassive neutron star forms and initially is a stable configuration against the gravitational collapse. Later a delayed gravitational collapse is induced by the energy dissipation through gravitational waves, e.g. Shibata et al. (2006); see also Oechslin et al. (2007). The collapse again leads to formation of hot, magnetized torus surrounding a rotating BH with the outer radius of high density region much smaller than 20 km, and in this case the expected lifetime of the torus is only  $\sim 10$  ms. The detailed predictions likely depend on the assumptions about the magnetic field (see e.g. Liu et al., 2008) but in general the agreement of the predicted timescales and observed properties of VSB are in this case satisfactory.

### 3.2.2. *evaporation of primordial black holes*

The primordial black holes discussed here as a possible origin of the very short bursts should have masses in the range of  $10^9 - 10^{14}$  g, depending on time of their evaporation. The constraints for the abundance of the holes contribution to the dark matter density in the Universe, depending on their masses was recently discussed by Lacki and Beacom (2009) in a broad range of masses. The observed gamma-ray background limits the contribution of PBH to the critical density of the Universe to  $\Omega_{PBH} < 10^{-8}$ , which was already set by Page and Hawking (1976), and similar results are obtained nowadays (Carr et al., 2010). The limits for the somewhat larger PBH masses, obtained from the Milky Way neutrino, electron-positron and gamma ray backgrounds are constraining the total abundance of PBHs in the Universe and their contribution to the dark matter density, although the limits are less stringent (Lacki and Beacom, 2009,  $\Omega_{PBH} < 10^{-4}$  for PBH masses between  $2 \times 10^{15}$  g to  $1000 M_{\odot}$ ). Abramowicz et al. (2009) studied the possible observational signatures of PBHs in the mass range of  $10^{16} - 10^{26}$  g via their collisions with stars in our Galaxy, and found that the X-ray signals produced in such events would be too weak or too rare to be observable.

The identification of the VSB with the evaporating black holes does not violate those constraints. If the signal is indeed due to evaporating black holes, the typical distance to the source can be estimated in the following way. The initial mass of the black hole evaporating now is of the order of  $5 \times 10^{14}$  g, depending on the details of the evaporation efficiency at the later (hadron) stages. Nevertheless, most of the mass disappears during the initial slow evaporation. The mass of the black hole at the final stages, 0.1 s before the hole disappearance, is only about  $6 \times 10^8$  g. If its energy is finally fully converted to photons and they reach BATSE detectors as  $\sim 100$  keV the registration of a thousand photons would place the source at a distance of  $\sim 2$  pc. Typical

distance estimates were a factor of 100 larger (see e.g. Cline et al., 2005) since they were based on the initial PBH mass of  $5 \times 10^{14}$  g. The numbers of VSB in the BATSE catalog, roughly 10 per year, thus imply the average rate of 0.3 gamma ray flashes per cubic pc. We assume an initial steep power law distribution of the black hole masses (with a power law index larger than 2), and we take into account the mass evolution in time due to evaporation. The number of observed flashes is obtained from integration over the mass distribution from the minimum mass evaporating now ( $6 \times 10^8$  g at the final 0.1 s) to the mass which will evaporate after a year ( $4 \times 10^{11}$  g). Comparing this theoretical rate with the observed number of bursts we derive the normalization constant of the mass distribution. Integrating over the whole mass distribution, we obtain mass density of PBH equal  $7 \times 10^{-39}$  g cm<sup>3</sup>, i.e.  $\Omega_{PBH} \approx 10^{-9}$ .

One of the expected properties of the black hole evaporation is the uniformity of the phenomenon. Black hole loses its angular momentum during the initial slow stage of the evaporation (before the loss of 10 per cent of the mass). Thus the only parameter describing the evaporating black hole is its mass. If the number of particles released in a considered time unit is large, every event should look identically. The details of the emission process and the expected final radiation spectrum from the fireball-type last stages have been considered in a number of papers (for the review see e.g. Bugaev, 2009). Although the predictions differ with respect to the energy peak of the spectrum as well as the spectral slope in the gamma-ray range, none of the papers predict any departure from isotropy of the emission, and consequently, from the identical look of all events.

Our sample of VSB shows a variety of shapes, thus the events are not identical. This means that either the primordial black hole evaporation origin is ruled out, or the evaporation process is in need of a considerable revision.

Such a revision is likely to come. As argued by MacGibbon et al. (2008), the interaction between the particles emitted by evaporating black hole is probably not as strong, as considered in a number of previous papers (e.g. Kapusta, 2001; Daghigh and Kapusta, 2002); see Bugaev et al. (2008) for a review. If the particles finally escaping the gravity field of evaporating black hole move radially, since only almost purely radial velocity allows to leave the black hole vicinity, and the evaporation process proceeds through quark jets, there is indeed no thermalization involved at the beginning of the process and local fluctuations (i.e. in emission in various directions) may be large. The total energy of a VSB registered by an instrument (BATSE, in our case) is less than 1 erg per event, and thus all the registered emission of a given burst is likely to come from a single jet-like event close to a black hole horizon. If this is the case, then the events do not have to be exactly identical, prone to the initial quark ejection as well as tiny differences with respect to the inclination of a specific jet. However, they nevertheless should be short and hard, as already argued by Cline and Hong (1992), thus consistent with the VSB properties.

We fitted to the composite VSB data the time profile of the optically thin fireball emitted in the final stage of the black hole evaporation. The rise timescale is in this case given by the analytic function,  $L(t) \propto t^{-2/3}$ , while the normalization is fitted to the gamma ray background level. Such a model well represented the shape of the composite profile. After the maximum, the fireball will have different time characteristics, since we can have the hadronization with jet production, direct gamma and graviton production, as well as a direct lepton production, and large fluctuations in this process may explain the shape variety. This the black hole evaporation model is also consistent with the data for VSB.

The tentative determination of the redshift for three VSB detected by SWIFT does not automatically rule out the evaporation scenario, because the connection with the candidate galaxies is only claimed by the proximity of the objects on the sky and may be a projection effect. However,

a long X-ray fading tail of the GRB 050509B discussed in Sect. 3.1 may indeed be difficult to explain within the evaporation scenario.

#### 4. Conclusions

We studied the sample of the BATSE gamma ray bursts, limited to the special group of VSB ( $T_{90} < 0.1$  s). These bursts seem to originate in a special region in our Galaxy, however we found that their arrival is statistically consistent with being uniform in time. The time profiles of these bursts are asymmetric, with one or two peaks. We found no correlation between the burst asymmetry and its hardness, as well as no clear evidence for the time lags between the hard and soft photons.

We found that the burst properties are most likely to be consistent with two origin mechanisms. The first plausible mechanism is the binary NS-NS merger with low total masses passing through a phase of hypermassive neutron star. The second one is the evaporation of a primordial black hole in the scenario of no photosphere formation.

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